

# The Galactic disk mass-budget:

## II. Brown dwarf mass-function and density.

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## ABSTRACT

In this paper, we extend the calculations conducted previously in the stellar regime (Chabrier, 2001) to determine the brown dwarf initial mass function in the Galactic disk. We perform Monte Carlo calculations taking into account the brown dwarf formation rate, spatial distribution and binary fraction. Comparison with existing surveys seems to exclude a power-law mass function as steep as the one determined in the stellar regime below  $1 M_{\odot}$ , i.e.  $dn/dm \propto m^{-1.5}$ , and tends to favor a more flatish behaviour. Although a power-law mass function in the substellar regime can not be excluded by present day observational constraints, a form  $dn/dm \propto m^{-1}$ , i.e.  $dn/d \log m = \text{constant}$ , seems to be an upper limit. Comparison with methane-dwarf detections tends to favor an eventually decreasing form like the lognormal or the more general exponential distributions determined in the previous paper. We calculate predicting brown dwarf counts in near-infrared color diagrams and brown dwarf discovery functions for various types of mass functions and formation rates, and for different binary distributions. Based on these diagnostics, future large deep field surveys should be able to determine more precisely the brown dwarf mass function and to provide information about the formation of star-like objects - stars and brown dwarfs - along the Galactic history. These calculations yield the presently most accurate determination of the brown dwarf census in the Galactic disk. The brown dwarf number density is comparable to the stellar one,  $n_{BD} \simeq n_{\star} \simeq 0.1 \text{ pc}^{-3}$ , showing that the star formation process in the disk extends well into the substellar regime. The corresponding brown dwarf mass density, however, represents only about 10% of the stellar contribution, i.e.  $\rho_{BD} \lesssim 5.0 \times 10^{-3} M_{\odot} \text{ pc}^{-3}$ . Adding up the local stellar density determined in the previous paper, we obtain the density of star-like objects, stars and brown

dwarfs, in the solar neighborhood  $\rho_{\odot} \approx 5.0 \times 10^{-2} M_{\odot} pc^{-3}$ .

*Subject headings:* Dark matter, low-mass stars, brown dwarfs, luminosity function, mass function

## 1. Introduction

Brown dwarfs (BD) - objects not massive enough to sustain proton fusion in their core - were once thought to be the most favorable candidates to make up for the Galactic missing mass. Indeed their luminosity is orders of magnitude fainter than the Sun and a Salpeter-like mass function (MF) extending into the BD domain would yield a large mass-to-light ratio and thus a significant amount of baryonic dark matter in the Galactic disk or halo. Although this scenario is now clearly excluded, a proper census of the number of BDs in the Galaxy has significant implications for our understanding of how star-like objects form and for an accurate determination of the contribution of substellar objects to the Galaxy mass budget, more particularly in the disk. Since by definition BDs never reach thermal equilibrium and formed at several epochs during the evolution of the Galaxy, this task requires not only the determination of the BD initial mass function (BDIMF), i.e. the extension of the stellar IMF below the hydrogen-burning limit, but also of the BD birthrate. The determination of these quantities from today BD observable signatures implies the knowledge of BD evolution, i.e. accurate relations between mass, age, and observable quantities such as magnitudes and colors.

Observations of BDs in the solar neighborhood have progressed at a rapid pace within the past few years. The DENIS (Delfosse et al., 1999) and 2MASS (Kirkpatrick et al. 1999; Burgasser et al. 1999) surveys, which have covered initially areas of several hundred square degrees and are complete to  $K \simeq 13.5$  and  $K_S \simeq 14.5$ , respectively, have first revealed about 20 field L-dwarfs and 4 field methane-BDs. This yields an L-dwarf number-density  $n_L \approx 0.03 \text{ (sq deg)}^{-1}$  for  $K_S < 14.5$  and a methane-BD (also denominated T-dwarfs) number-density  $n_{CH_4} \approx 0.002 \text{ (sq deg)}^{-1}$  for  $J < 16$ , with large uncertainties. These determinations have improved with subsequent L-dwarf and T-dwarf discoveries with the Sloan survey (Strauss et al., 1999; Tsvetanov et al., 2000; Leggett et al., 2000), the NTT

Deep Field (Cuby et al., 1999) and with the extension of the 2MASS survey which covers now about 10% of the sky with a color-selection criterion  $J - K_s \geq 1.3$  (Kirkpatrick et al., 2000). These surveys bring the number of discovered L- and T-dwarfs to over 100 and about 10, respectively, almost half of the L-dwarfs and most of the T-dwarfs being suspected to lie within  $\sim 25$  pc from the Sun. Even though statistics is still small, these numbers provide important observational constraints on the present-day BD number-density in the Galactic disk.

A first attempt to determine the BD density and BDIMF has been conducted recently by Reid et al. (1999). Although these calculations certainly point the way, they rely on BD models primarily devoted to the description of Gl-229B like objects (i.e. methane-BDs) (Burrows et al., 1997) and thus do not apply to the characteristics, spectroscopic or photometric signature, of L-dwarfs. Moreover, they rely on dubious color- $T_{eff}$ -bolometric correction relations, and thus suffer from inconsistencies in the mass-age-magnitude-color relations. At last, these calculations assume one single form for the IMF, namely a power-law function. It is the aim of the present paper to improve upon these calculations by using consistent BD evolutionary calculations and by considering several possibilities for the BD Galactic history, mass function, birthrate and binary frequency. The IMF in the stellar regime has been determined in a previous paper (Chabrier, 2001, hereafter Paper I) down to the vicinity of the H-burning limit, providing the normalization at this limit to extend into the BD domain. This stellar IMF has been shown to be adequately fitted by three different functional forms over the entire stellar mass-range. These functional forms, however, behave quite differently in the BD regime. While the power-law function keeps rising monotonically, the two other forms - lognormal or exponential - slowly decline in the substellar domain below a characteristic mass. We thus expect the density of BDs to differ appreciably, depending on the form of the adopted BDIMF, at least between a power-law as the one determined in Paper I and a lognormal or exponential form. The present

calculations should help distinguishing between these two generic forms in the low-mass domain, power-law or lognormal, by comparison with available BD observations. For a sake of completeness, we also conduct calculations with a power-law form with  $\alpha = 1$ , i.e.  $dn/d\log m = \text{constant}$ , in the substellar regime. We calculate the predicted BD discovery function (BDDF) and BD counts associated with these different IMFs for large-field surveys at faint magnitude. These predictions will serve as a guide to analyze or to design future surveys aimed at determining the stellar and brown dwarf local densities and Galactic history.

In §2, we briefly comment on the BD models used in the present calculations. In §3, we outline the calculations and describe the BD mass, age, spatial and binary probability distributions. The predicted BD counts and BDDF, and comparisons with existing surveys, are presented in §4. The derived BD number- and mass-densities in the Galactic disk are presented in §5, which yields the presently most accurate determination of the stellar+BD density in the solar neighborhood. Section 6 is devoted to the conclusion.

## 2. Brown dwarf evolutionary models

### 2.1. From L-dwarfs to T-dwarfs

Brown dwarfs are now identified as belonging to two main spectral types, the so-called "L-dwarf" and "methane-dwarf" types, the latter being also denominated "T-dwarf". The L-dwarfs are characterized by very red near infrared colors, with  $J - K \gtrsim 1.0$ , a consequence of the formation of grains near their photosphere, whereas the second population exhibits bluer near infrared colors, with  $J - K \lesssim 0.5$ , due to the dominant absorption of methane overtone bands in the 1.0 to 2.5  $\mu\text{m}$  range (H and K bands) (see e.g. Figure 9 of Kirkpatrick et al., 2000). The effective temperature range characteristic of the L-dwarf population

remains ill-determined. Basri et al. (2000), using a  $T_{eff}$ - $Sp$  classification based on the analysis of CsI and RbI lines with a preliminary set of synthetic spectra of Allard et al. (2001), obtain a range  $T_{eff} \approx 1600 - 2200$  K, consistent with the values obtained with evolutionary models in color-magnitude diagrams (Chabrier et al., 2000a), whereas the more empirical  $T_{eff}$ - $Sp$  relation derived by Kirkpatrick et al. (1999) yields a cooler temperature range  $T_{eff} \approx 1300 - 2000$  K. New analysis of Keck HIRES spectra with improved dusty-atmosphere models are in reasonable agreement with the Basri et al. (2000) determination (Schweitzer et al., 2001). Although it is still premature to settle for one of these two determinations, recent observation of the onset of methane absorption in the L-dwarf 2M1507 (Noll et al., 2000) tends to support the former scale. Indeed the weakness of the  $\nu_3$  methane band in this object, and in 2M0825, suggests a temperature significantly higher than the  $\text{CH}_4$ -CO equilibrium temperature  $T \simeq 1200 - 1400$  K under BD atmosphere conditions (photospheric pressure  $P_{ph} \sim 3 - 10$  bars) (Tsuji et al 1995; Fegley & Lodders, 1996), a value which would result from the Kirkpatrick et al. (1999) determination.

As argued by Kirkpatrick et al. (1999), their temperature scale yields a temperature gap of  $\sim 350$  K between the faintest observed L-dwarf Gl584C and the T-dwarf Gl229B, for a  $\sim 0.4$  magnitude difference, whereas the Basri et al. (2000) scale corresponds to about twice this temperature gap. Although such an argument is certainly relevant, the quantitative result must be considered with caution for several reasons. First of all, the temperature gap relies on  $T_{eff}$  estimated from the spectral type, i.e. the energy spectral distribution only. However, grain formation in L-dwarf atmospheres yields a severe backwarming effect. Therefore, the difference in the *thermal structure* of the atmosphere between an L-dwarf and a T-dwarf atmosphere, where most grains are suspected to form or settle much below the photosphere, is already significant (see e.g. Figure 1 of Chabrier et al., 2000a). It would be no surprise that this grain settling effect yields by itself a considerable decrease in  $T_{eff}$  between (dusty) L-dwarfs and (almost grainless) Gl229B-like

objects. The quantification of this effect must await atmosphere models including grain sedimentation. The other possible flaw in the Kirkpatrick et al. (1999)  $T_{eff}$  determination stems from their estimate of the absolute magnitude of Gl584C. This latter is determined from a  $M_J$  or  $M_K$  vs  $Sp$  relationship based on the Kirkpatrick et al. (1999) L-dwarf spectral classification. Until this classification is proven unambiguously to be the correct one, the magnitude determination must be taken with great caution. At last, these authors assume the same mass,  $\sim 0.045 M_\odot$ , and the same age,  $\sim 0.5$  Gyr, for Gl584C and Gl229B, two rather arbitrary assumptions. The  $M_J$  magnitude of L-dwarfs with mass  $m \sim 0.05 M_\odot$  varies by about 6 magnitudes between 0.1 and 1 Gyr, not mentioning the strong variation of magnitude with mass (see e.g. Chabrier et al., 2000a).

The more recent  $T_{eff}$ - $Sp$  relationship for early L-dwarfs of Schweitzer et al. (2001) and the spectroscopic analysis of Leggett et al. (2001) suggest that dust settling in the atmosphere of L-dwarfs should start around  $T_{eff} \sim 1700$ -1800 K, and that the limit case illustrated by the so-called "dusty" atmosphere models should no longer be used below about this temperature. We will respect this constraint in the present models (see §2.2). A much more robust, severe constraint for the transition from L-dwarfs to T-dwarfs is the null detection of objects with  $J - K \gtrsim 2.1$  in all surveys, covering about 10% of the sky, whereas objects fainter than the ones at this limit have been discovered, all with T-dwarf characteristic  $J - K \sim 0$  (Kirkpatrick et al., 2000).

More recently, objects with weak  $\text{CH}_4$  absorption features in the H and K bands have been discovered with the Sloan survey (Leggett et al., 2000) with intermediate colors  $0.5 \lesssim J - K \lesssim 1.0$  and  $0 \lesssim H - K \lesssim 0.5$  and have been identified as early T-dwarfs.



## 2.2. The models

The BD evolutionary models used in the present calculations are described in Chabrier et al. (2000a) and in Chabrier & Baraffe (2000). The first set of models are the so-called "dusty" models, based on the recent Allard et al. (2001) atmosphere models which include grain formation in the atmosphere equation-of-state (EOS) and grain opacity in the radiative transfer equation. These models successfully reproduce the observed colors and magnitudes of the afore-mentioned L-dwarfs near the bottom of the main sequence (Chabrier et al., 2000a), as well as their spectral energy distribution (Leggett et al., 2001; Schweitzer et al., 2001). The second set of models, so-called "cond" models, include grain formation in the atmosphere EOS, thus taking into account the corresponding element depletion, but ignore the grain opacity. This case mimics a rapid settling of grains below the photosphere and reproduces reasonably well the colors and magnitudes of Gliese229B and methane BDs (see Chabrier et al., 2000a and figure 13 of Chabrier & Baraffe, 2000).

In order to compute a complete evolutionary sequence over the entire BD range from the hydrogen-burning limit  $m \simeq 0.07 M_{\odot}$  down to a Jupiter mass  $0.001 M_{\odot}$ , we have used the dusty-models for  $T_{eff} \geq 1700$  K and the cond-models for  $T_{eff} \leq 1350$  K, based on the arguments discussed in §2.1, and we have smoothly interpolated between these two limits for objects with effective temperatures in-between.

These models provide consistent relationships between mass, age, effective temperature, colors and magnitudes for the disk BD population, avoiding dubious transformations of  $M_{bol}$  or  $T_{eff}$  into observable quantities. Although still far from an accurate description of the various phenomena at play in L-dwarf and T-dwarf atmospheres, and thus from a robust description of their observational signatures for a given mass and age, they reproduce quite well, as mentioned above, the only robust observational constraints on these objects, namely magnitudes and colors, in the two limit cases of hot, dust-dominated L-dwarfs

and Gl229B-like or cooler methane-dwarfs, respectively. In particular in near-infrared colors, the relevant spectral domain for BD detection. Indeed, the effective temperature itself is not the issue in the present calculations; it is used only to interpolate between L-dwarfs and methane-dwarfs. The main uncertainty occurs obviously for the objects in this interpolated region, where there is presently only one object with determined parallax and thus absolute magnitude (Els et al., 2001). The present models reproduce quite well this important constraint both in  $M_J$  vs  $J-H$  and  $M_J$  vs  $J-K$  color-magnitude diagrams, respectively within and at the limit of the observational error bar, for an age  $t \sim 1$  Gyr, the expected age of the system. This brings confidence in our interpolation procedure. Note that this domain of interpolation covers only about one magnitude in  $J$  (Chabrier et al., 2000a; Chabrier & Baraffe, 2000). As shown in §4, objects in this region correspond to a restricted combination of masses and ages, namely young low-mass BDs or older massive BDs, and represent only a minor fraction of the Galactic BD population. Given these facts, the present calculations should yield reasonably accurate determinations of the BD color and magnitudes in term of their age and mass.

### 3. The calculations

We use Monte-Carlo simulations to generate a sample of BDs with known mass, age and distance. The luminosity, effective temperature and colors are then given by the models described in §2. We also consider the possibility of BD binary systems, with various frequencies and mass ratios. This yields the Luminosity Function (LF) of the systems and of the resolved objects. The various stages of the calculations are outlined below.

### 3.1. Total number of objects in the simulations

The total number of objects  $N_{tot}$  in the simulated volume is:

$$N_{tot} = \Omega \times \left( \int_0^{d_{max}} n(r) r^2 dr \right) \times \left( \int_{m_{inf}}^{m_{sup}} \xi(m) dm \right) \quad (1)$$

where  $\Omega$  is the field of view,  $n(r)$  is the spatial distribution and  $\xi(m) = \frac{dN}{dm}$  denotes the initial mass function, i.e. the number of objects ever formed in the mass-interval  $[m, m + dm]$ . The first term in brackets in eqn.(1) is the volume integration. We use a standard double-exponential disk for the spatial density distribution:

$$n(z, R) = 1.0 \times e^{-\left(\frac{R-R_{\odot}}{L}\right) - \frac{\|z\|}{h}} \quad (2)$$

where  $z(l, b)$  and  $R(l, b)$  are the galactocentric cylindrical coordinates for longitude  $l$  and latitude  $b$ ,  $L \simeq 2500$  pc is the scale length,  $h \simeq 250$  pc the scale height (Haywood, Robin & Cr   , 1997) and  $R_{\odot} = 8.5$  kpc is the Sun galactocentric distance.

Note that the number-density normalization in eqn.(2) is set up to  $1 \text{ pc}^{-3}$ ; the mass-density normalization in the solar neighborhood is fixed by the observationally-determined value of the IMF at a given mass (eqn.(10) below) and thus by the integral of this IMF over the stellar+substellar mass range (see §3.3 and §5). For the simulations, we chose a characteristic distance limit for BD detection  $d_{max} = 100$  pc in eqn.(1), so that the number of objects in the simulations is  $\sim 10^6$ . Methane-BDs have been detected at about this distance with the NTT Deep Field survey (Cuby et al., 1999). The maximum mass for BDs, i.e. the minimum mass for stable hydrogen-fusion is  $m_{sup} \simeq 0.072 M_{\odot}$  (Chabrier & Baraffe, 1997) and the minimum mass is chosen to be  $m_{inf} = 0.001 M_{\odot}$ , about a Jupiter mass. For illustration, for a limit magnitude  $J_{lim} \sim 22$ , a distance limit  $d=100$  pc

( $M_J \simeq 17$ ) corresponds to the limit of detection of methane-BDs  $m \simeq 0.001 M_\odot$  at  $t \simeq 10^6$  yr,  $m \simeq 0.01 M_\odot$  at  $t \simeq 3 \times 10^8$  yr,  $m \simeq 0.02 M_\odot$  at  $t \simeq 10^9$  yr and  $m \gtrsim 0.05 M_\odot$  at  $t \simeq 10^{10}$  yr (Chabrier & Baraffe, 2000).

### 3.2. The brown dwarf initial mass function

The BDIMF is the extension in the substellar regime of the stellar IMF determined in Paper I. Unlike stars, which eventually evolve off the main sequence stage, BDs have unlimited lifetimes so that all BDs ever formed in the Galaxy still exist today, regardless on when they were formed, and the present day BD mass function is the BD initial mass function. We conducted the calculations with three different forms of IMFs, namely the power-law IMF labeled IMF1 in Paper I:

$$\xi(m) = \frac{dn}{dm} = A m^{-\alpha} \quad (3)$$

where  $n$  is the number-density of objects,  $A = 0.019 M_\odot^{-1} \text{pc}^{-3}$ ,  $\alpha = 1.55$  (see Paper I),

the lognormal IMF labeled IMF2 in Paper I:

$$\xi(\log m) = \frac{dn}{d \log m} = A \exp\left\{-\frac{(\log m - \log m_0)^2}{2 \sigma^2}\right\} \quad (4)$$

with  $A = 0.141 \text{ pc}^{-3}$ ,  $m_0 = 0.1 M_\odot$  and  $\sigma = 0.627$  (see Paper I).

As mentioned in Paper I, the lognormal form (4) and the exponential form (IMF3, eqn.(8) of Paper I) are barely distinguishable in the BD domain and yield very similar results.

For a sake of completeness, we have also performed calculations with a power-law with a shallower slope  $\alpha = 1.0$  in the BD domain, as suggested in previous calculations (Reid et al., 1999). To insure the continuity of the MF, the normalization is fixed at  $0.1 M_{\odot}$  at the value given by IMF1,  $dn/dm(0.1 M_{\odot}) = 0.674 M_{\odot}^{-1} \text{pc}^{-3}$ . This IMF, hereafter denoted IMF4, thus reads:

$$\begin{aligned} \xi(m) = \frac{dn}{dm} &= A \left( \frac{m}{0.1} \right)^{-1.55} & m \geq 0.1 M_{\odot} \\ &= A \left( \frac{m}{0.1} \right)^{-1.0} & m \leq 0.1 M_{\odot} \end{aligned} \quad (5)$$

with  $A = 0.674 M_{\odot}^{-1} \text{pc}^{-3}$

The total number-density of objects in the mass-interval  $[m_{inf}, m_{sup}]$  is

$$n = \int_{m_{inf}}^{m_{sup}} \xi(m) dm = \int_{\log m_{inf}}^{\log m_{sup}} \xi(\log m) d \log m \quad (6)$$

We suppose in the present calculations that the IMF does not depend on time and remained constant along the evolution of the Galactic disk.

### 3.3. The formation rate

We consider two types of star (more generally star-like object) formation rates (SFR), namely:

- a constant SFR:

$$b(t) = b_0 = \text{constant} \quad (7)$$

- a time-decreasing exponential SFR:

$$b(t) = b_0 e^{-\frac{t-t_{inf}}{\tau}} \quad (8)$$

with an e-folding time  $\tau = 5$  Gyr (Miller & Scalo, 1979).

The values of  $b_0$  obey the normalization condition  $\frac{1}{\tau_G} \int_{t_{inf}}^{\tau_G} b(t) dt = 1$ , where  $\tau_G \approx 10$  Gyr is the age of the Galactic disk and  $t_{inf} < \tau_G$  (Miller & Scalo, 1979; Scalo, 1986). The (roughly) constant SFR is the most favored solution for the disk history (see e.g. Scalo, 1986) but comparison with an exponential SFR is instructive, as shown below.

As mentioned previously, the normalization of the BDIMF in the present calculations is imposed by the number of objects observed today at a given mass, e.g. at the H-burning limit  $m \approx 0.07 M_\odot$ . The total number-density of star-like objects (stars plus BDs) ever formed in the Galactic disk is given by the integral of the creation function (Scalo, 1986):

$$n_{tot}(t = \tau_G) = \frac{1}{\tau_G} \int_0^{\tau_G} b(t) dt \times \int_{m_{inf}}^{\infty} \xi(m) dm = \int_{m_{inf}}^{\infty} \xi(m) dm \quad (9)$$

where the afore-mentioned normalization condition on the SFR has been applied and where we assume separability between the SFR and the IMF, so that the total density of objects per unit mass at the H-burning limit today is:

$$\frac{dn_{tot}}{dm}(m = 0.07 M_\odot) = \xi(m = 0.07) \quad (10)$$

This value corresponds to  $1.17 M_\odot^{-1} \text{ pc}^{-3}$  for IMF1 (eqn.(3)),  $0.85 M_\odot^{-1} \text{ pc}^{-3}$  for IMF2 (eqn.(4)) or IMF3 (see Paper I), and  $0.96 M_\odot^{-1} \text{ pc}^{-3}$  for IMF4 (eqn.(5)), respectively.

### 3.4. The probability distributions

For each object  $i = 1, N_{tot}$ , the Monte Carlo technique is used to determine:

- its age  $(\tau_G - t_i)$  with a probability law  $P(t) = \tau_G^{-1} \times \int_{t_{inf}}^t b(t') dt'$  where  $b(t)$  is the probability density given by either  $b(t) = constant$  or  $b(t) = e^{-\frac{t-t_{inf}}{\tau}}$ , with the normalization condition  $\tau_G^{-1} \times \int_{t_{inf}}^{t_{sup}} b(t) dt = 1$ . The lower and upper limits are chosen as  $t_{inf} = 10^6$  yr,  $t_{sup} = \tau_G$ .

- its distance  $r_i$  with a probability law  $P(r) = \int_0^r p(r') dr'$  where  $p(r)$  is the probability density  $p(r) = r^2 n(r)$ , for  $r = 0 \rightarrow d_{max}$ , and  $n(r)$  is given by eqn.(2).

- its mass  $m_i$  with a probability law  $P(m) = \int_{m_{inf}}^m p(m') dm'$  where  $p(m)$  is the probability density given either by the uniform distributions (3) or (5), or by the gaussian distribution (4), with the normalization condition  $\int_{m_{inf}}^{m_{sup}} p(m) dm = 1$ .

We consider also the possibility for a uniformly distributed fraction  $X_{BD}$  of BDs to have another BD companion. For the mass ratio between the secondary and the primary  $q(m) = \frac{m_2}{m_1} \leq 1$ , we have conducted the calculations with two different distributions, namely:

- a normal form:

$$P(q) = e^{-\frac{(q-m_c)^2}{2\sigma^2}} \quad (11)$$

where  $m_c = 0.23$  and  $\sigma = 0.42$  are taken from Duquennoy & Mayor (1991).

- a uniform distribution:

$$P(q) = constant \quad (12)$$

## 4. The results

The probability distributions described in §3.4 yield for each object  $i = 1, N_{tot}$  its mass  $m_i$ , age  $\tau_G - t_i$ , distance  $d_i$ . The properties  $T_{eff_i}$ ,  $\log g_i$ , absolute magnitude  $M_i$ , apparent magnitude  $m_{ap_i}$ , and colors are given for each  $(m_i, t_i)$  by the models described in §2.2. The afore-mentioned probability distributions give also the number  $N_{bin} = X_{BD} \times N_{tot}$  of BDs with a companion of mass  $m_{i_2} = q(m).m_{i_1}$ . The apparent magnitudes of the *systems* in a filter  $\lambda$  are derived from the values of the two unresolved companions:

$$m_{ap_\lambda}(sys) = m_{ap_\lambda}(m_1) - 2.5 \log\{1 + 10^{\frac{m_{ap_\lambda}(m_1) - m_{ap_\lambda}(m_2)}{2.5}}\} \quad (13)$$

This yields the so-called systemic distribution.

For a survey with a magnitude-limit  $m_{ap_{lim}}$ , only the objects with  $m_{ap_i} \leq m_{ap_{lim}}$  are considered in the results of the simulation.

### 4.1. Comparison with existing surveys

In order to test the validity of our calculations, we first confront the theoretically predicted numbers with existing surveys. Such results are given in Table I. The DENIS survey (Delfosse et al., 1999) has a field-of-view  $\Omega = 240$  sq.deg, a magnitude limit  $K_{lim} \simeq 13.5$ . It is expected to detect L-dwarfs up to a distance  $d_{max} \simeq 30$ -35 pc, although the exact volume probed by BD surveys is not well determined, since  $d_{max}$  strongly varies with the mass and the age of each BD. The 2MASS survey (Kirkpatrick et al., 1999; Burgasser et al., 1999) had originally  $\Omega = 371$  sq.deg.,  $K_{S_{lim}} \simeq 14.5$  ( $K_{lim} \simeq 15$ ) (see Table 3 of Kirkpatrick et al., 1999) and should detect L-dwarfs up to about 50 pc, with a color selection criterion  $J - K > 1.3$ . It has been extended recently to about 10% of the sky,



i.e.  $\Omega \simeq 4000$  sq.deg.,  $K_{lim} \simeq 15$  (Kirkpatrick et al., 2000; Burgasser, 2000). Almost half of the detected L-dwarfs are suspected to lie within 25 pc from the Sun, although the distances are estimated from the Kirkpatrick et al. (1999) absolute magnitude vs spectral type relation and must be considered with caution. Only 17 L-dwarfs have measured parallaxes. This survey, however, is likely to be substantially incomplete (D. Kirkpatrick, private communication) so that the number of L-dwarfs detected in the whole survey given in Table 1 is certainly largely underestimated. The incompleteness is clearly illustrated by the comparison between observation and theory or by a simple scaling between the two 2MASS fields. From our calculations, most of these L-dwarfs are found to lie within about 50 pc from the Sun.

Other surveys like the Sloan Digitized Sky Survey (Strauss et al., 1999; Tsvetanov et al., 1999; Leggett et al., 2000) and the ESO NTT survey (Cuby et al., 1999) have also discovered several L-dwarfs and methane-dwarfs in the solar neighborhood. Note that for methane-dwarfs, the color selection used by 2MASS,  $J-H \leq 0.3$ ,  $H-K \leq 0.3$ , eliminates early (hot) methane-dwarfs, in the L/T BD transition domain, as the ones discovered by SDSS, in spite of the smaller volume probed by this survey. The majority of the T-dwarfs identified by 2MASS and SDSS have  $J \sim 15-16$ , making them detectable up to about 12 pc for Gl229B-like objects ( $T_{eff} \approx 1000$  K) (see Chabrier et al., 2000a). The number of objects found by these different surveys are given in Table I.

For this comparison we consider only the case of a constant SFR (eqn.(7)). The case of a time-decreasing SFR will be examined in §4.2.4. A number of BD binary systems have been resolved observationally in the afore-mentioned surveys. For the conditions of these surveys and a BD binary fraction  $X_{BD} = 0.3$ , however, the numbers of theoretically predicted detections of systems or resolved objects are not significantly different ( $\sim 10\%$ ). For L-dwarf detections, we used  $m_{sup} = 0.08 M_{\odot}$ . Indeed, very-low-mass hydrogen-burning stars, with

$0.072 M_{\odot} < m \lesssim 0.08 M_{\odot}$  and  $t \gtrsim 1$  Gyr reach effective temperatures characteristic of the L-dwarf type (see e.g. Fig. 16 of Chabrier & Baraffe 2000 or Tables 3-5 of Chabrier et al. 2000a).

The comparison between theory and observations in Table I should be taken with caution. Statistics is still small, models still uncertain, the true BD binary fraction presently unknown and the exact limit magnitudes of the survey not well established. In spite of these uncertainties, some information can be drawn. The L-dwarf surveys seem to favor the lognormal IMF2 or the shallower power-law IMF4, the IMF1 predicting a substantially larger number of objects than observed. However, as illustrated by the 2MASSII survey, large fields are necessary to really distinguish between these forms if only L-dwarfs are considered. The T-dwarf detections, however, seem to exclude the IMF1, which overestimates significantly the number of T-dwarfs detected by 2MASS. The lognormal form IMF2 yields also a good agreement with T-dwarf observations, whereas the number of T-dwarfs predicted with IMF4 appears to be overestimated. A more robust determination between these two latter forms, however, needs larger statistics.

#### 4.2. Brown dwarf mass, age and temperature distributions

In this section we conduct predictive calculations for large, deep field surveys, which should yield enough statistics to determine more precisely the shape of the BDIMF. We also examine the predicted distributions of BD masses, ages and effective temperatures as a function of magnitudes and colors. We define the following reference model:

$$X_{BD} = 0.30 ; P(q) = constant ;$$

and reference survey:

$$J_{lim} = 22 ; \Omega = 100 \text{ sq.deg.}$$

It is instructive to examine the expected mass-, age- and  $T_{eff}$ -distributions of the BDs as a function of near infrared magnitudes or colors for the conditions mentioned above. Figure 1 displays the distribution of objects with  $m \leq 0.08 M_{\odot}$  for IMF1, IMF2 and IMF4. As expected, the IMF1 predicts a significantly larger number of BDs, in particular of very-low-mass BDs, below the deuterium-burning minimum mass  $m_D \simeq 0.012 M_{\odot}$ . The IMF1 predicts about 80 of these objects in our reference survey whereas IMF4 predicts about 20 and only a few are predicted to be visible with IMF2. This provides an interesting diagnostic on the shape of the BDIMF. This requires, however, the spectroscopic observation of the presence of deuterium at faint magnitude, a delicate, although achievable task (Chabrier et al., 2000b). Note that young ( $\lesssim 10^7$  yr) BDs above the deuterium-burning minimum mass have not burned their deuterium yet (Chabrier et al., 2000b, Figure 1), but the relative contribution of such young objects in the field is statistically negligible (see below).

Figure 2 displays the BD age-distribution in  $J-K$  colors obtained with IMF1 and IMF2. As seen in the figure, there is a noticeable accumulation of young L-dwarfs, with  $t \lesssim 10^8$  yr, redward of  $J-K \gtrsim 0.8$ . This reflects the cumulative contributions of massive ( $\gtrsim 0.05 M_{\odot}$ ) BDs and of very young ( $t \lesssim 10^7$  yr) BDs near the deuterium burning minimum mass ( $m \lesssim 0.03 M_{\odot}$ ). Deuterium-burning keeps these objects hot enough ( $T_{eff} > 2000$  K) to exhibit late-M and L-dwarf colors (see Chabrier et al., 2000b, Figure 1 and Chabrier et al., 2000a, Figure 6). More massive BDs will burn their deuterium content at earlier ages and the number of such very young objects is statistically insignificant. The statistically dominant BD population in the color diagram lies blueward of  $J-K \sim 0$ , which corresponds to  $T_{eff} \lesssim 1400$  K (see Figure 4). This is the consequence of both the contribution of lower

mass BDs (see Figure 1) and of BD cooling, since, as seen in Figure 2, the BD distribution is largely dominated by objects with an age  $t > 10^9$  yr . As a consequence of these two statistically favorably populated regions in the color diagram, respectively redward of  $J-K \sim 0.9$  and blueward of  $J-K \sim 0.5$ , there is a relative scarcity of objects in the region in-between. This is clearly illustrated in Figure 3 which displays the BD distribution for the two IMFs as a function of  $J-K$  color. For samples with low statistics, as for presently existing surveys, this scarcity can lead to a gap, with no object discovered in this color interval. The age-distribution obtained with IMF1 exhibits the same qualitative behaviour as with IMF2, except for a larger number of young ( $< 10^8$  yr) T-dwarfs ( $J-K < 0.5$ ), as expected from the larger number of very-low mass BDs (see Figure 1).

Figure 4 displays the  $T_{eff}$  vs  $J-K$  relation for the predicted BD distribution. Note in passing the presence of a few hot ( $T_{eff} \geq 2500$  K) genuine BDs ( $m \leq 0.07 M_{\odot}$ ). These objects have a V-magnitude  $M_V \lesssim 16$ . Therefore, some of the faintest objects identified as very-low-mass stars in the local sample may in fact be young, bright BDs, yielding a BD contamination of the last bin(s) of the 5-pc nearby LF, as suggested in Paper I.

### 4.3. Predicted brown dwarf discovery function

In this section we calculate the predicted BDDF for the reference survey mentioned in §4.2<sup>1</sup>, and we examine the dependence of this DF upon the different inputs for BD Galactic history, IMF, SFR and binary frequency.

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<sup>1</sup>In this paper, we stick to the following definitions: the luminosity function is the number of objects per absolute magnitude interval whereas the discovery function is the predicted number of objects to be found by a survey of given area and limited magnitude, as considered in the present section

#### 4.3.1. *Effect of the IMF*

Figure 5 compares the systemic apparent BDDF in the J-band  $\Phi_{J_{sys}}$  obtained with the BDIMFs IMF1, IMF2 and IMF4, respectively. The sudden increase of the BDDF around  $J \sim 17$  stems from the onset of the T-dwarf contribution, as illustrated by the dotted and dashed lines, respectively, for IMF1 and IMF2. As expected from the larger number of predicted low-mass BDs, the number of faint objects predicted with the steeply rising IMF1 is significantly larger than with the two other forms. As expected from Figure 1, the number of L-dwarfs ( $J \lesssim 17$ ) predicted with IMF2 and IMF4 is comparable, but this latter form predicts almost twice as many T-dwarfs. The T-dwarf to L-dwarf ratio amounts to  $n_T/n_L \approx 7$  with IMF1,  $n_T/n_L \approx 5$  with IMF4 and  $n_T/n_L \approx 3$  with IMF2. Large field photometric surveys at faint magnitude should thus be able to provide important information on the shape of the BDIMF, simply by looking at the faint end of the distribution and at the  $n_T/n_L$  ratio.

#### 4.3.2. *Effect of the SFR*

Figure 6 compares the systemic apparent DFs  $\Phi_{J_{sys}}$  obtained with IMF1 and IMF2, respectively, for two different SFRs, namely a constant SFR (eqn.(7)) and an exponentially decreasing SFR (eqn.(8)). As expected, the latter one yields a significantly smaller number of bright BDs since the majority of the objects formed several billion years ago and have now dimmed to very faint magnitudes. The corresponding signature on a color-magnitude diagram will be a smaller number of L-dwarfs. Indeed, BD counts done with the decreasing SFR for the conditions of the DENIS and 2MASS-I surveys (see Table 1) predict 6 and 14 L-dwarfs, respectively, with IMF1, and 4 and 7 L-dwarfs with IMF2. The number of T-dwarfs is also significantly diminished and the combination of the exponentially-decreasing SFR and the steep IMF1 yields a creation function which brings the predicted counts in

reasonable agreement with both the observed L-dwarf and T-dwarf detections.

#### 4.3.3. *Effect of binarity*

Although the frequency of BDs in multiple systems is presently very poorly determined, a few general trends emerge from the various existing searches:

- BDs seem to be very rare as close companions ( $\lesssim 100$  AU) of nearby F, G and M stars, confirming the so-called "brown dwarf desert" at *small separation* (Halbwachs et al., 2000). However BDs exist as wide companions ( $\sim 100 - 4000$  AU) of solar-type stars ( $M_V < 9.5$ ,  $Sp = F-M0$ , i.e.  $m \gtrsim 0.5 M_\odot$ ). No wide BD companion has been detected so far for lower mass stars. Although the fraction of such BDs is still very uncertain, Gizis et al. (2001) estimate this fraction to be  $f_{BD} \approx 5 - 30\%$ , which large uncertainties due to small statistics. From the stellar IMF determined in Paper I, the number density of solar-type stars with  $m \gtrsim 0.5 M_\odot$  is  $\sim 0.02 \text{ pc}^{-3}$ . With the afore-mentioned estimated value of  $f_{BD}$ , this yields a number density of BD as star companions  $n_{BD\star} \approx 1.0-6.0 \times 10^{-3} \text{ pc}^{-3}$  and an estimated mass density  $\rho_{BD\star} \leq n_{BD\star} \times 0.07 \lesssim 0.5 \times 10^{-3} M_\odot \text{ pc}^{-3}$ , within at least a factor of 2 uncertainty. A better determination of this fraction of BDs as wide companions of stars should emerge in the near future.

- About  $\sim 20\%$  of L-dwarfs have an other L-dwarf companion. In contrast to BDs companions of stars, these L-dwarf binaries have small ( $\lesssim 10$  A.U.) separations, whereas wider BD-BD systems are lacking (Reid et al., 2001). Several of the L-dwarf binaries discovered originally in the DENIS and 2MASS surveys prove to be equal-luminosity, and thus equal-mass systems, although it is still premature to draw robust conclusions about the primary/secondary mass ratio.

Figure 7 compares the systemic (unresolved) and the single (resolved) apparent J-band

DFs obtained with  $X_{BD} = 0.30$  for three companion mass-distributions, namely a uniform mass-ratio distribution (eqn.(12); long-dash line), a gaussian distribution (eqn.(11); dotted line), and an equal-mass distribution  $q(m) = 1$  (short-dash line). For a sake of clarity, only calculations with IMF2 are displayed. As seen in the figure, the correction on the systemic DF due to unresolved companions amounts at most to a factor of  $\sim 30\%$  at the faint end for the equal-mass case under the presently defined survey conditions.

## 5. Brown dwarf number-density and mass-density

The BD total number-density in the Galactic disk field  $n_{BD}$  is given by eqn.(6). We must add the contributions arising from BD companions in BD binary systems  $n'_{BD} = X_{BD} \times n_{BD}$  and from BD companions of main sequence stars  $n_{BD\star}$  (§4.3.3).

Similarly, the BD total mass-density in the Galactic disk is given, for an equal-mass distribution for the BD companions, by:

$$\rho_{BD} = (1 + X_{BD}) \times \int_{0.001}^{0.07} \xi(m) m dm + \rho_{BD\star} \quad (14)$$

Table 2 gives the corresponding numbers for the most favorable BDIMF IMF2, and for the IMF4, obtained for a constant SFR for a BD-BD binary fraction  $X_{BD} \approx 0.3$  with a mass-ratio  $q(m) = 1$  and a BD-star binary fraction  $f_{BD} = 0.05-0.3$ . The corresponding BD surface densities are obtained for a disk scale height  $h = 250$  pc.

The present calculations and the ones derived in Paper I yield the presently most accurate determination of the density in the solar neighborhood under the form of stars and brown dwarfs. From Table 2 of Paper I and Table 2 of the present paper, one gets the local normalization for the disk  $\rho_{\odot} \simeq (4.5 + 0.5) \times 10^{-2} \simeq 5.0 \times 10^{-2} M_{\odot} pc^{-3}$ ,

$\Sigma_{\odot} \simeq (24.5 + 2.0) \simeq 26.5 M_{\odot} pc^{-2}$ , within about  $\pm 10\%$ .

## 6. Conclusion

In this paper we have extended the stellar initial mass function determined in a previous paper (Chabrier, 2001) into the brown dwarf domain. With this mass function, we have performed Monte Carlo calculations, taking into account the brown dwarf formation rate along the Galaxy history, the brown dwarf spatial distribution in the disk and the possibility for brown dwarfs to belong to binary systems with different frequencies and mass ratio distributions. The calculations have been performed with the two different functional forms for the mass function in the low-mass regime determined in Paper I, namely a power law  $dN/dm \propto m^{-1.5}$ , i.e. a linear log-log distribution, or a gaussian-type (lognormal) distribution  $dN/d\log m \propto \exp\{-\frac{1}{2\sigma^2} \log(\frac{m}{m_0})^2\}$ , both normalized to the observed stellar density at the bottom of the main sequence. We have also performed calculations with a shallower power-law MF below  $0.1 M_{\odot}$ ,  $dN/dm \propto m^{-1.0}$ , i.e  $dN/d\log m = \text{constant}$ . As shown in Paper I, the lognormal distribution is well reproduced in the low-mass domain by a more general exponential form. Whereas the power law increases monotonically in the brown dwarf regime, predicting an increasing number of objects per mass interval with decreasing mass, the lognormal and the exponential forms eventually turn down below a characteristic mass, about the hydrogen-burning minimum mass in  $dN/d\log m$  (see Figure 4 of Paper I), i.e. about the deuterium-burning minimum mass  $m \simeq 0.012 M_{\odot}$  in  $dN/dm$ . Comparison with existing L-dwarf and methane-dwarf detections tends to exclude the continuation into the substellar regime of the power-law determined in the stellar domain, which predicts a number of BDs significantly larger than observed, at least for a constant star formation rate along the disk evolution. The shallower power-law yields a number of L-dwarfs in agreement with the observations but seems to predict too many T-dwarfs,



although better statistics is needed to really nail down this issue. These results show that a slope  $\alpha = 1$  is probably about the upper limit for a power law fit of the IMF in the brown dwarf domain. Comparison with the observations seems to favor the lognormal form, i.e. the general exponential form. As mentioned above, these results hold for a constant SFR. Degeneracy arises from various combinations of the IMF and the SFR. Indeed a time-decreasing SFR combined with a steep BDIMF can lead to BD counts comparable with the ones produced by a constant SFR and a shallower IMF. A nearly constant formation rate along the disk history, however, seems to give the best representation of the high mass star distribution (see e.g. Miller & Scalo, 1979) and of the distribution of chromospheric activity in the local stellar population (Henry, Soderblom & Donahue, 1996).

These results tend to support a flattening of the Galactic field stellar mass function  $dN/d\log m$  around the H-burning limit. Although statistics is presently insufficient to accurately determine the exact shape, i.e. the values of the various coefficients, of the mass function in the substellar regime, future large, deep field surveys should allow such a determination, in particular by comparing the relative contributions of the bright and faint parts of the brown dwarf luminosity function, and the photometrically identified ratio of methane dwarfs over L-dwarfs.

Rapid progress both on the theoretical and the observational sides should quickly remove the remaining uncertainties in the present calculations. These latter present the first determination of a general, time-independent mass function, which seems to adequately describe the formation of star-like objects in the Galactic disk from about  $100 M_{\odot}$  down to about  $10^{-3} M_{\odot}$ , i.e. five orders of magnitude in mass, even though some uncertainty remains at very-low-masses between a slowly rising power-law (with  $\alpha < 1$ ) and a lognormal form, because of presently limited statistics of field T-dwarf detections. If the general exponential form is confirmed, leading to a power-law form at large masses and a lognormal

distribution at low masses, it supports the suggestion that the formation of stars obeys a self-similar, statistically determined fragmentation process with no peculiar characteristic mass. In that case, neither the hydrogen-burning nor the deuterium-burning limits should play a peculiar role, but it is noteworthy that the number of objects per mass-interval in the lognormal or exponential distributions appear to turn down below about this latter limit.

Integration of this brown dwarf IMF yields the presently most reliable determination of the BD census in the Galactic disk and of its contribution to the Galactic disk mass budget. A significant source of uncertainty, however, stems from the yet undetermined contribution of BD companions of either other BDs or of stars at wide separations. Comparison with the values determined in Chabrier (2001) for the stellar contribution shows that the BD population in the disk is comparable to the stellar one,  $n_{BD} \simeq n_{\star} \simeq 0.1 \text{ pc}^{-3}$ , for the favored mass function IMF2, so that the star formation process extends well into the substellar regime. The BD mass contribution to the disk budget, however, amounts only to about  $\sim 10\%$  of the stellar mass-density. Adding up the present determination and the previously determined stellar contribution yields the Galactic disk local density of star-like objects  $\rho_{\odot} \simeq 0.05 M_{\odot} \text{ pc}^{-3}$ .

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Table 1: L-dwarf and T-dwarf detections for different surveys. In columns 4 and 5, "obs" is the observed number of objects while "MF1", "MF2" and "MF4" denote the number of objects obtained with the IMF1, IMF2 and IMF4, respectively. The references are: (1) Delfosse et al. (1999); (2) Basri et al. (2000); (3) Kirkpatrick et al. (1999); (4) Kirkpatrick et al. (2000); (5) Burgasser (2000); (6) Tsvetanov et al. (2000); (7) Leggett et al. (2000). The magnitudes are the ones in the standard UKIRT system.

Survey	$\Omega$ (deg <sup>2</sup> )	mag. lim.	L-dwarfs (J-K $\gtrsim$ 1.0) obs/MF1/MF2/MF4	T-dwarfs ) (J-K $\lesssim$ 1.0) obs/MF1/MF2/MF4
<b>DENIS</b> <sup>(1),(2)</sup>	240	K $\leq$ 13.5	5/13/6/7	
<b>2MASSI</b> <sup>(3)</sup>	371	K $\lesssim$ 15; J-K > 1.3	19/35/18/22	
<b>2MASSII</b> <sup>(4)</sup>	$\sim$ 4000	K $\lesssim$ 15, J-K > 1.3 d $\leq$ 25 whole survey	42/50/27/30 $\sim$ 100/400/180/240	
<b>2MASSII</b> <sup>(5)</sup>	18360	K $\lesssim$ 14.5, J-H $\leq$ 0.3, H-K $\leq$ 0.3		13/88/27/42
<b>SDSS</b> <sup>(6)</sup>	130	z <sup>*</sup> $\lesssim$ 19, J $\lesssim$ 16		2/6/2/3
<b>SDSS</b> <sup>(7)</sup>	225	z <sup>*</sup> $\lesssim$ 19, J $\lesssim$ 16		3/10/3/5

Table 2: Disk present-day brown dwarf density in the Galactic disk calculated with the BDIMF IMF2 (upper row) and IMF4 (lower row). The scale height for the determination of the surface density is 250 pc.

	$n_{\star}$ (pc <sup>-3</sup> )	$\rho_{\star}$ (M <sub>⊙</sub> pc <sup>-3</sup> )	$\Sigma_{\odot}$ (M <sub>⊙</sub> pc <sup>-2</sup> )
BD systems	0.09	$3.0 \times 10^{-3}$	1.5
	0.28	$4.6 \times 10^{-3}$	2.3
BD-BD companions	0.03	$1.0 \times 10^{-3}$	0.5
	0.09	$1.5 \times 10^{-3}$	0.8
$(X_{BD} = 0.3, q(m) = 1)$			
BD-star companions	$1.0\text{-}6.0 \times 10^{-3}$	$\lesssim 0.5 \times 10^{-3}$	$< 0.5$
$(f_{BD} = 0.05\text{-}0.3)$			
all BDs	$\sim 0.12$	$\sim (4.0\text{-}4.5) \times 10^{-3}$	$\sim 2$
	$\sim 0.37$	$\sim (6.0\text{-}6.5) \times 10^{-3}$	$\sim 3$

## FIGURE CAPTIONS

Fig. 1.— Mass distribution for objects with mass  $0.001 \leq m/M_{\odot} \leq 0.08$  obtained with the power law IMF1 (dash line), the power law IMF4 (dash-dot) and the lognormal IMF2 (solid line) for  $J \leq 22$  and  $\Omega = 100$  sq.deg.

Fig. 2.— Age distribution as a function of J-K colors for the reference survey conditions, for IMF1 (upper figure) and IMF2 (lower figure), respectively

Fig. 3.— Brown dwarf distribution as function of J-K colors for IMF1 (dash line) and IMF2 (solid line) for  $J \leq 22$

Fig. 4.— Brown dwarf effective temperature distribution

Fig. 5.— Predicted systemic brown dwarf discovery function obtained with the IMF1 (long-dash line), the IMF4 (dash-dot line) and the IMF2 (solid line). The dotted and short-dash lines display the T-dwarf contributions for IMF1 and IMF2, respectively

Fig. 6.— Predicted systemic brown dwarf discovery function obtained with the IMF1 and IMF2, for a constant SFR (eqn.(7); long-dash and solid lines) and an exponentially-decreasing SFR (eqn.(8); dot and short-dash line)

Fig. 7.— Predicted brown dwarf discovery function obtained with IMF2 and a constant SFR for the unresolved systems (solid line) and for the resolved objects for  $X_{BD} = 0.30$ , for a companion uniform mass-distribution (eqn.(11); long-dash line), gaussian mass-distribution (eqn.(12); dotted line) and equal-mass distribution ( $q(m) = 1$ ; short-dash line)















